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On the wind energy resources of Sudan

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Abstract

The imminent exhaustion of fossil energy resources and the increasing demand for energy were the motives for those reasonable in Sudan to put into practice an energy policy based on rational use of energy; and on exploitation of new, and renewable energy sources. After 1980, as the supply of conventional energy has not been able to follow the tremendous increase of the production demand in rural areas of Sudan, a renewed interest for the application of wind energy has shown in many places. Therefore, the Sudanese government began to pay more attention to wind energy utilisation in rural areas. Because the wind energy resource in many rural areas is sufficient for attractive application of wind pumps, and as fuel is insufficient, the wind pumps will be spread on a rather large scale in the near future. Wind is a form of renewable energy, which is always in a non-steady state due to the wide temporal and spatial variations of wind velocity. A number of years worth of data concerning wind speed in Sudan have been compiled, evaluated and presented in this article. The need for the provision of new data stations in order to enable a complete and reliable assessment of the overall wind power potential of the country is identified and specific locations suggested. This paper presents the background and ideas of the development of the concept as well as the main results, and experience gained during ongoing project up to now. In Sudan, various designs of wind machines for water pumping have been developed and some designs are presently manufactured commercially. Results suggest that wind power would be more profitably used for local-and small-scale applications especially for remote rural areas. It is concluded that Sudan is blessed with abundant wind energy.

Keywords: Sudan; Wind energy resources; Wind power potential and assessment; Wind pumps application; Water pumping

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1. Introduction

New and renewable sources of energy can make an increasing contribution to the energy supply mix of Sudan in view of favourable renewable energy resource endowments, limitations and uncertainties of fossil fuel supplies, adverse balance of payments, and the increasing pressure on environment from conventional energy generation. Among the renewable energy technologies, the generation of mechanical and electrical power by wind machines has emerged as a techno-economical viable and cost-effective option.

The use of wind pumps declined dramatically from the 1920s due to the economic depression and the use of electric motors or petrol and diesel engines to drive water pumps. Soaring energy prices in the 1970s and growing interest in renewable energy sources led to their reconsideration, particularly in Sudan, although the take-up of the technology is still slow. This had led to the following developments:

- the attempts to disseminate wind pumps;
- adoption of modern engineering analysis and design methods; and
- a new generation of low cost modern wind pumps has evolved but it has as yet not reached the level of reliability of the old classical wind pumps.

The provision of pumped clean water is one of the best ways to improve health and increase the productive capacity of the population. Rural access to clean water is best

achieved through pumping from underground water aquifers rather than using surface water sources, which are often polluted. Because of the relatively small quantities of water required, wind pumping for village supply and livestock watering can is cost-effective given a good wind site. Irrigation pumping, however, requires large quantities of water at specific times of the year. For much of the year the pump may be idle or oversized and wind pumping for irrigation may be more difficult to justify on economic grounds.

Wind pumps have been proceeding in Sudan since the 1950s for the purposes of pumping water, for drinking, and irrigation in remote desert areas-Gezira region, the Red sea hills along the main Nile north of Khartoum down to Wadi Halfa. These wind machines are of the Southern Cross types and suffered from several problems. None of them is now working [1]. Since 1975 there has been a revival by incorporating new technologies into the designs (generators, electronics, control systems, etc.). Ten wind pumps types consultancy services wind energy developing countries (CWD)—Holland was installed around the Khartoum area (some of them were working until now) [2]. The main competitions to wind pumps are diesel pumps sets and solar pumps. Using a diesel engine costs less to buy and easier to site, but requires frequent maintenance, an operator and the diesel fuel. Combining diesel with wind power may bring benefits in some situations. The use of solar energy to power electric pumps has become a reliable and simple technology, and more details are given by Markvart [3]. Solar panels or photovoltaic modules convert the sun's radiation directly into electrical energy to drive the pump set. Solar pumps are expensive to buy initially but require little maintenance and no fuel. As with wind pumping, the relative economics depend on the level of the resource, i.e., sunlight, at a particular site.

Wind energy is one of the several energy sources alternatives to the conventional primary energy resources, which now power man's industrial and socio-economic activities worldwide. With the notable exception of hydropower (which in fact is renewable) these primary energy resources have definite lifetimes, depending on use rate among several other factors.

The presented work on development of a mechanical wind pump has going on in Sudan for several years. It is based on a multi-bladed rotor with high efficiency. The aim has been to develop a wind pump, which needs limited service, and maintenance; and meets for mass production in Sudan. Wind energy use in Sudan should therefore be directed at slow-running turbines, with attention paid to system reliability, cost reduction and site selection if the tremendous political, social and economic inertia about wind (and other renewable) energy is to be overcome. The market is growing but it relies on a number of small manufacturers, who have limited possibilities and support for research, product and market development [4].

2. Objectives

This article sheds light on the possibilities of utilising wind energy in Sudan, and focuses on the viability of manufacturing wind pumps locally. The work is limited to few locations/sites in the country, and results of one reliable site (Soba) have been included in the discussion. Also, the work was limited to one make/type of wind pumps (CWD 5000), but reflections on other makes (Kijito) have been considered. Wind energy for water pumping was the main aim; no other use was included in the research.

3. Energy sources

Sudan is the largest country of the African continent, with an area of approximately one million square miles ($2.5 \times 10^6\,km^2$). It extending between latitudes 3°′N and 23°′N, and longitudes 21°45′E and 39°′E. Sudan is a relatively sparsely populated country. The total population according to the 1999 census was 34.5×10^6 inhabitants. The growth rate is 2.8%/y, and population density is 14 persons/km^2. Sudan is rich in land and water resources [5]. Sudan like most of the oil importing countries suffered a lot from sharp increase of oil prices in the last decades. Spending most of its hard currency earnings in importing oil, but could not meet the increasing demand. Oil bill consumes more than 50% of the income earnings. The oil share is only 12% of the total energy consumption. Biomass (wood-fuel, agricultural residues and animal waste) utilised as fuel source is dominating Sudan's energy picture, accounting for about 87% of the country total energy consumption [6]. The electricity sector represented at most 1% of the total energy supplies (55% from hydropower and 45% from thermal generation) [7]. The household sector consumed 60% of the total electricity supplies.

Renewable energy technologies such as solar, wind, biomass, etc., become more important since there are local resources and indefinite sources of energy. Renewable energy needs, especially in rural areas and small communities. Renewable sources of energy are regional and site specific. The renewable strategy is well integrated in the National Energy Plan [8] and clearly spelled out in the National Energy Policy, but this is not enough. It has to be integrated in the regional development plans. The role of renewable is big in solving essential life problems especially in rural areas for people and their resource development like the availing of energy for the medical services for people and animal, provision of water, education, communication and rural small industries [9]. The main source of energy which are applicable in Sudan for rural now are solar, wind and biomass for small power supplies for households, rural electrification, communications and special applications, health centres, potable water and irrigation. Sudan is in the process of developing its comprehensive energy policy [10]. The main thrust of this policy will be to lower the cost of energy to the community, in the broadest sense of the term. Other goals are to ensure the reliable supply of energy and potable water, to diversify the fuel mix to attenuate foreign dependence and to conserve energy. Aspects of environmental concern and some use of renewable energy must be included [10].

Renewable energy technologies such as wind have great potential for improving water supply in rural areas. If promotion is adequately planned and put into effect, the technology could assist to alleviate the heavy burden that women face in their search for water. Although wind pumps have been in use for decades in Sudan, a lot of work has been done to develop the large-scale wind energy application for the provision of clean drinking water and sanitation. It has long been recognised that water plays a pivotal role in human life. Accordingly, the government has defined programmes that accord high priority to rural water development because the water supply situation is unbearable. More than 70% of the rural population has not access to reasonable water supply, which is obtained, from protected wells, boreholes and small piped water supply schemes. Water from rivers although considered unsafe for direct consumptions, is widely used as a traditional. Water supply in rural areas is one of the most critical needs. Women are faced with the heavy burden of fetching water from considerable distances from home. The technology would provide a potential for increased production of say vegetables. From an environmental

point of view, wind energy also offers an attractive option to water provision in relation to use of fossil fuels, e.g., diesel. It does not produce any pollutants like carbon monoxide, nitrogen oxides and hydrocarbons, which are associated with fossil fuels. Besides, the wind power is an inexhaustible energy source that is naturally renewable. Government should consider a 'water pumping wind machines programme' as an infrastructure building programme and should both encourage village co-operatives and set up agencies for installing and maintaining wind pumps in view of the environmental benefit.

4. Analysis and assessment methodologies

Three basic methods have been used in wind energy resource assessments:

- statistical and subjective analysis of existing wind measurements, other meteorological data and topographical information;
- qualitative indicators of long-term wind speed levels; and
- application of boundary layer similarity theory and the use of surface pressure observations.

In general, wind data in summarised or digitised formats are preferred. For stations having several different types of summarised wind data covering various time periods, one or two of the better summaries for those stations should be selected considering:

- the most suitable format for wind power assessment;
- the longest record;
- the least charge in anemometer evaluation and exposure; and
- the most frequent daily observations.

In many remote areas wind data may be sparse or non-existent and evaluation of the wind data may have to rely on qualitative rather than quantitative methods. For example, there are topographic/meteorologic indicators of both high and low wind power classes. The following are some indicators of a potentially high wind power class:

- gaps, passes and gorges in areas of frequent strong pressure gradients;
- long valleys extending down from mountain ranges;
- plains and plateaus at high evaluations;
- plains and valleys with persistent down slope winds associated with strong pressure gradients;
- exposed ridges and mountain summits in areas of strong upper-air winds;
- exposed coastal sites in areas of strong upper-air winds or strong thermal pressure gradients.

Features generally indicative of low mean wind speeds are as follows:

- valleys perpendicular to the prevailing wind a lot;
- sheltered basins;
- short and/or narrow valleys and canyons;
- areas of high surface roughness (e.g., forested hilly terrain).

5. Statistical distribution for wind data

5.1. Methods of analysis

Available wind data from the Meteorological Department (Khartoum) were used. The data were subsequently stratified according to quality, based on the following factors:

- accuracy of the recording equipment and techniques;.
- type of data collected;
- exposure of the recording equipment;
- recording period (year);
- recording rate/interval.

5.2. Adjustment of evaluation

Due to the anemometers at different meteorological stations being set at different levels, the measurements, prior to analysis, have to be adjusted to the same height. The standard height, according to the world meteorological organisation (WMO), is 10 m above ground level [11]. This height is adopted in the following analysis. There are two methods that can be used to adjust the wind velocity at one level to another level. One of them is the application of power law and the other is to employ the logarithmic law.

5.3. Power law

Power law is a mathematical relation representing measured wind speed profile in turbulent boundary layer. This relation is expressed as

$$(V_1/V_2) = (h_1/h_2)^n, \tag{1}$$

where V_1 is wind speed at height h_1 in turbulent boundary layer, V_2 is free stream wind speed, h_2 is boundary layer thickness, and n is power law exponent.

Practically, the wind speed at any height Z is adjusted to the speed at Z reference. The equation, then, becomes

$$(V_{\mathrm{ref}}/V_Z) = (Z_{\mathrm{ref}}/Z)^n \tag{2}$$

or

$$V_{\mathrm{ref}} = V_Z(Z_{\mathrm{ref}}/Z)^n. \tag{3}$$

Power law exponent varies depending on the surface roughness. It has a value of 0.14 for calm sea, 0.4 for town [12]. In 1978, Smedman-Högström and Högström [13] proposed a relationship between the exponent n and the surface roughness Z_o. Their proposed relation, deduced from the experimental results, also includes the stability of the atmosphere. This relationship can be mathematically written as

$$n = C_o + C_1 \log Z_o + C_2 \log Z_o, \tag{4}$$

where C_o, C_1 and C_2 vary with the stability of the atmosphere, Z_o is the surface roughness length, which are shown in Tables 1 and 2.

Table 1
Roughness of height for different types of terrain

Terrain	Types	Roughness height Z_o (m)
Flat	Ocean, landscape, beach	0.005
Open	Low grass, airports, high grass, low crops	0.03
Rough	Tall row crops	0.25
Very rough	Forests	0.50
Closed	Villages	1.00
Towns	Town centre, open spaces in forests	>2.0

Table 2
Values of the constants C_o, C_1 and C_2 of the Eq. (4) for n as a function of $\log Z_o$

Stability class	C_o	C_1	C_2
1, 2. Unstable	0.18	0.13	0.03
3. Near neutral	0.30	0.17	0.03
4. Slightly stable	0.52	0.20	0.03
5. Stable	0.80	0.25	0.03
6. Very stable	1.03	0.31	0.03

A number of effects have to be considered:

(1) *Wind shear*: The wind slows down, near the ground, to an extent determined by the surface roughness.
(2) *Turbulence*: Behind buildings, trees, ridges, etc.
(3) *Acceleration* (*or retardation*): On the top of hills, ridges, etc.

Wind flowing around buildings or over very rough surfaces exhibits rapid changes in speed and/or direction, called turbulence. This turbulence decreases the power output of the wind machine and can also lead to unwanted vibrations of the machine. Generally, the effect is stronger when the ridge is rather smooth and not too steep nor too flat. The orientation of the ridge should preferably by perpendicular to the prevailing wind direction. If the ridge is curved it is best if the wind blows in the concave side of the ridge. A quantative indication of acceleration is difficult to give, but increases of 10–20% in wind speed are easily attained. Isolated hills give less acceleration than ridges, because the air tends to flow around the hill. This means that in some cases the two hillsides, perpendicular to the prevailing wind, are better locations than top.

The power output of wind rotor increases with the cube of the wind speed. This means that the site for a wind machine must be chosen very carefully to ensure that the location with highest wind speed in the area is selected. The site selection is rather easy in flat terrain but much more complicated in hilly or mountainous terrains. The manipulations are meant to facilitate the judgement to what extent a given location might be suitable for the

utilisation of wind energy. In this respect, interest in the following:

- the daily, monthly and annual wind pattern;
- the duration of low wind speeds and high wind speeds;
- the expected locations must be not too far from the place of measurements;
- the maximum gust speed;
- the wind energy produced per month and per year.

5.4. Logarithmic law

Logarithmic law is the equation using physical arguments and experiment in analysis, which is

$$(V_Z/V_*) = 1/k\ \ln(Z/Z_o), \quad (5)$$

where V_* is friction velocity, V_Z is the wind speed at height Z, k is Von Karman constant, equals to 0.4, Z_o is the surface roughness length which can be found from [14]. Monin and Obukov [15] modified Eq. (5) by including the stability of the atmosphere. Their modified equation becomes

$$V_Z = V_*/k[\ln Z/Z_o - \Phi(Z/L)], \quad (6)$$

where $\Phi(Z/L)$ is a function with value varying with the stability of the atmosphere. For examples:

Stable condition

$$\Phi(Z/L) = -4.7\,Z/L, \quad (7)$$

where ($1/L > 0.003\,\mathrm{m}^{-1}$).

Neutral condition

$$\Phi(Z/L) = 0, \quad (8)$$

where ($-0.003 < 1/L \leqslant 0.003\,\mathrm{m}^{-1}$)

Unstable condition

$$\phi\left(\frac{Z}{L}\right) = 2Ln\left(\frac{1+X}{2}\right) + Ln\left(\frac{1+X^2}{2}\right) - 2\tan^{-1}\left(X + \frac{\pi}{2}\right), \quad (9)$$

where $X = (1-10\ Z/L)^{1/4}$; ($1/L < -0.003\,\mathrm{m}^{-1}$). L is called Monin and Obukov length; it depends on both the shear stress and heat flux.

Determination of the position on the earth surface for evaluating the surface roughness: Eq. (5) requires the value of surface roughness. However, in order to get the value of surface roughness, it is necessary to fix the area that has an influence on wind profile at the level to be adjusted. Smedman-Högström and Högström [13] derived the relationship between the growth of the internal boundary layer, Z_X and the distance from the discontinuity, X from the analysis of Pasquill [16]:

$$Z_X = aX^b, \quad (10)$$

in which, a and b are constants which vary with stability and surface roughness.

5.5. Available wind energy

The power available (P_a) in cross sectional area A perpendicular to the wind stream moving at speed V is

$$P_a = 0.5\rho A V^3, \tag{11}$$

where ρ is the air density.

Sometime available wind energy is expressed as power density:

$$P_a/A = 0.5\,\rho\,V^3. \tag{12}$$

However, wind machines can utilise not all of this power. The amount of power, which can be extracted from the wind stream, depends on the available wind energy and on the operating characteristics of the wind energy extraction device. The power output P of a wind energy conversion system, which subtends area A of the wind speed V, and density ρ is

$$P = 0.5\alpha C_p \rho A V^3, \tag{13}$$

where C_p is the power coefficient, $\alpha = 16/27 = (0.593)$ is the maximum efficiency of the Betz limit, ρ is the air density (kg m^{-3}), the density of the air depends on the temperature and on the altitude above sea level. For Sudan it is 1.15 kg m^{-3} [17], A is the total frontal area of the wind machine rotor (m^2) and V is undisturbed wind speed (m s^{-1}). The maximum extractable monthly mean wind power per unit cross sectional area, P, is given by [18]

$$P = 0.3409\,V^3, \tag{14}$$

where P is in W m^{-2}.

The constant 0.3409 takes Betz limit [19] into account and is derived from the factors given by Golding [20]. This analysis procedure is similar to that reported by Lysen [21].

5.6. Weibull distribution

In recent years much efforts has been made to construct an adequate statistical model for describing the wind frequency distribution. Most attention has been focused on Weibull function, since this give a good fit to the experimental data [22]. Weibull distribution is characterised by two parameters: shape parameter, K and scale parameter, C. The probability density function is given by

$$F(V) = (K/C)(V/C)^{K-1} \exp.[-(V/C)^K], \tag{15}$$

where V is the wind speed, K is the shape parameter and C is the scale parameter.

And the cumulative distributions function by

$$F(V) = \exp.[-(V/C)^K], \tag{16}$$

where V is the wind speed.

The mean of the distribution, i.e., the mean wind speed, V is equal to

$$V = C\Gamma(1/K + 1), \tag{17}$$

where Γ is the gamma function.

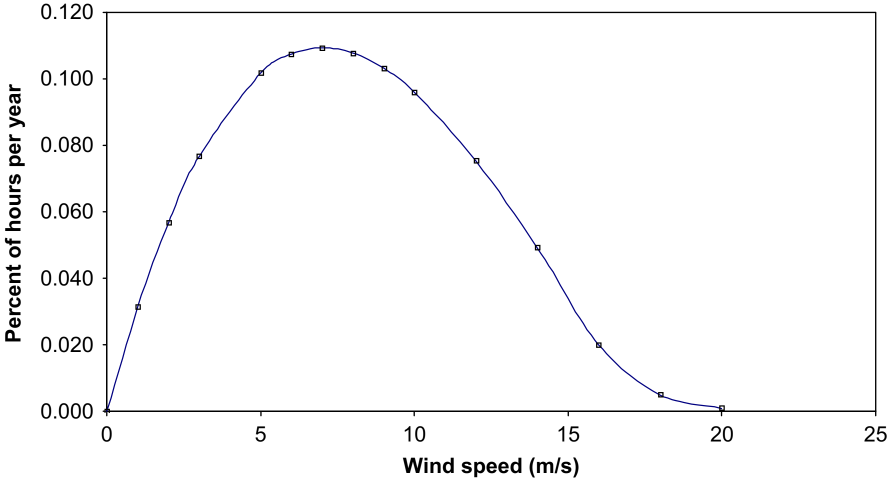

Fig. 1. Yearly wind probability density ($k = 1.99$, $c = 7.81\,\mathrm{m\,s^{-1}}$.

Defining a reduced wind speed

$$X = v/V, \tag{18}$$

where v is the average wind speed, and V is an accumulative wind speed parameter.

The probability density function can be rewritten as

$$F(X) = K\Gamma^K(1 + 1/K)X^{K-1}\ \exp.[-\Gamma^K(1 + 1/K)X^K], \tag{19}$$

and the cumulative distributions function as

$$F(X) = 1 - \exp.[-\Gamma^K(1 + 1/K)X^K]. \tag{20}$$

There are several methods for determining the Weibull distribution parameters, for example, the method of moment, the method using the energy pattern factor, the method of maximum likelihood and the method of least square fit of the cumulative probabilities [22,23]. Fig. 1 shows yearly wind probability density.

6. Available wind data

Consideration has been given to the consistent and effective presentation of data. Original data were extracted from published reports by Sudan Meteological Department (SMD) and converted into more useful working units, i.e., wind speed in miles per hour to $\mathrm{m\,s^{-1}}$. A total of 70 stations recorded the relative data available on wind speed and ambient temperature. Wind energy data consists of mean monthly wind speeds and wind directions measured at a height of 10 m above ground from stations throughout Sudan. Relatively accurate and properly maintained anemometers collected data. Vanes and Dines pressure-tube anemographs were used to record hourly mean wind speeds at 23 stations, other stations used beamfort estimates [24]. For most of the stations, the recording period was greater than 10 year and average recording intervals of an hour were satisfactory.

Monthly wind speed frequency distribution was also tabulated. The major parameter affecting the accuracy of the data was the exposure of the recording equipment to climate conditions, accordingly ca. 6% of the stations throughout the country were ignored in the analysis on grounds of inaccuracy. These data were utilised to determine annual wind speed frequency distribution, a major parameter in computing wind power density at a given site.

Anemometers were mounted on poles at a fixed height above ground, usually 5, 10 or 15 m. Under normal conditions, wind speed was greater at higher distance above ground. This is largely because the effects of surface features and turbulence diminish as the height increases. The variability depends on distance from the ground and roughness of the terrain [25]. It is much more difficult to predict average monthly wind speeds if the reference height at which the data were recorded is less than 6 m. Data collected at heights of less than 6 m should not be used to select a windmill or predict performance [26]. In relatively flat areas with no trees or buildings in the immediate vicinity, site selection is not critical [27]. However, in mountain areas or places where obstacles may block the flow of wind, differences in surface roughness and obstacles between anemometer and pump site must be taken into account when estimating wind speeds for the site. In Sudan, unequal measuring heights at different stations, in towns like Khartoum, Wad Madani, Atbara and El Obeid were measured at 15 m, in semi-towns at 10 m, and in the remaining at 5 m [28]. The accuracy of the instruments was estimated to 5%.

7. Wind energy potential in Sudan

The objectives of creating a wind resource database for Sudan are to:

- analyse the wind energy potential in Sudan using available wind data for the country;
- refine recorded data and develop an accurate estimate of global wind energy available in Sudan;
- identify wind characteristics required for the design of wind energy conversion systems.

Data, obtained from the Meteorological Department Office, were from measurements with cup anemometers coupled to chart recorders for selected stations. Mean monthly wind speeds were tabulated for 70 meteorological stations and mean annual wind powers were derived. Based on these data, an isovent map was developed showing the distribution of wind speeds all over the country (Fig. 2), so indicating the potential for wind energy in Sudan. Due to local conditions, there may be many high-wind sites in low-wind areas and conversely at a given site can be several times less than that calculated on the basis of mean annual wind speeds. This is due to the cubic power in the relationship between wind power and wind speed. The wind potential in Sudan is proportional to the latitude; the higher the latitude, the greater wind potential. In other words the regions below $9^{\circ\prime}$N (tropical region) have lower wind potential than the region above $9^{\circ\prime}$N. In the analysis of the data there were remarkable discrepancies for these reasons:

- growth of trees around the station and new buildings;
- quality of the maintenance and calibration of the measuring equipment;
- replacement of measuring equipment by another type.

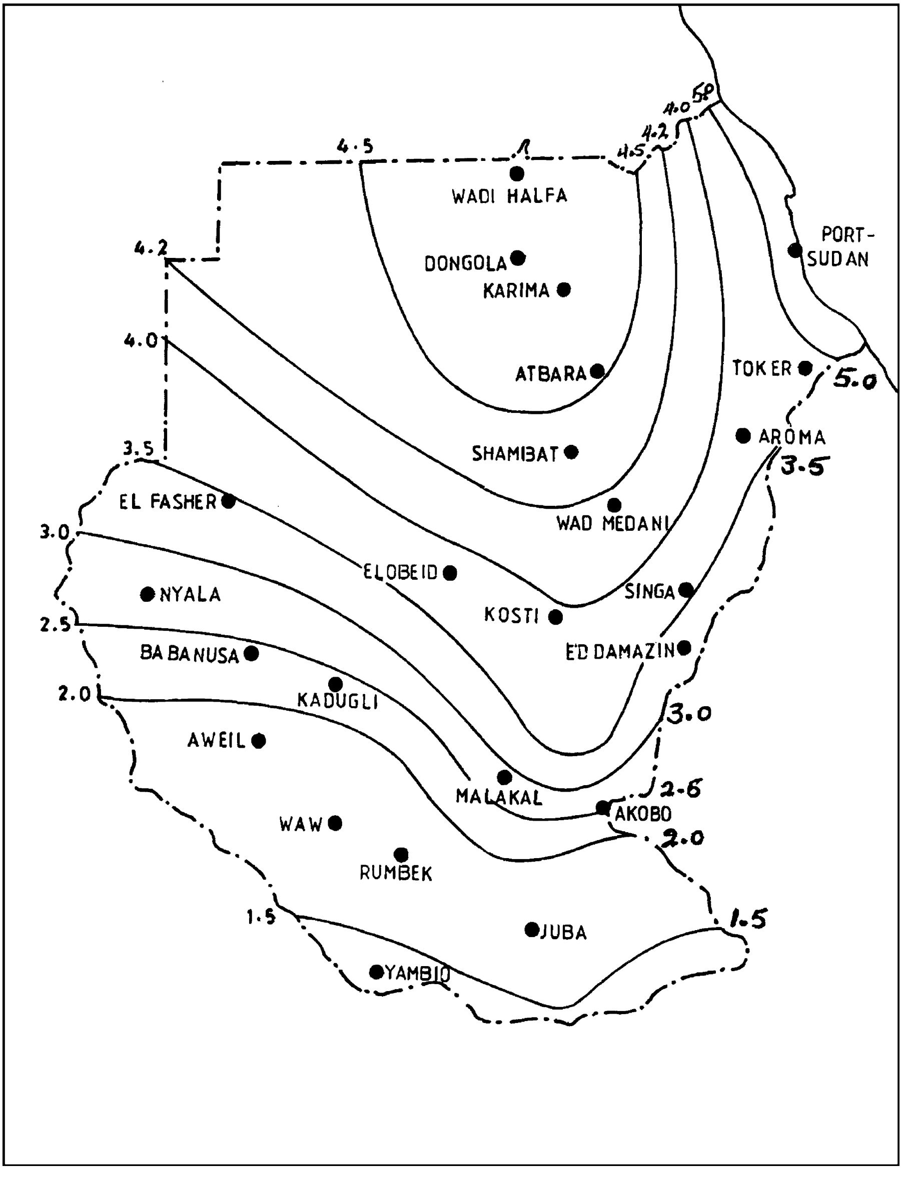

Fig. 2. Annual average wind speeds in Sudan ($m\,s^{-1}$).

The mean monthly wind speeds and wind directions measured at a height of 10 m above ground for stations throughout Sudan are given in [5]. It was found that the Weibull distribution gives a good approximation for many wind regions in Sudan. The resulting shape factor k and average wind speed are presented in Table 3, indicating large wind variability in Sudan. Most cases with very stormy winds in Sudan result from three kinds of storms [29,30]:

- Haboob (squalls), i.e., dust storms associated with cumulus clouds (cd) which occur in the period April–September.

Table 3
Results of Weibull parameters for number of Stations

Station	Altitude (m)	Annual wind speed (V) ms^{-1}	Shape factor (k)	Number of years of observation
Wadi Halfa	190	4.6	1.8	4
Port Sudan	5	5.0	1.6	10
Karima	250	4.7	1.7	10
Atbara	345	4.2	1.75	10
Shambat	380	4.8	2.1	10
Khartoum	380	4.8	1.9	10
Kassala	500	4.0	1.95	10
Wad Madani	405	4.8	1.8	10
El Fasher	733	3.4	1.15	10
El Geneina	805	3.1	1.9	10
El Obeid	570	3.4	1.9	10
Kosti	380	4.0	1.8	10
Abu Na'ama	445	3.1	2.2	10
Malakal	387	2.8	1.2	10
Wau	435	1.7	1.2	10
Juba	460	1.5	1.4	10

Table 4
The maximum gust speed recorded using Dines pressure tube anemograph

Station	Latitude (°)	Longitude (°)	Maximum gust speed ($m\,s^{-1}$)	Testing period
Wadi Halfa	21°56′N	31°31′E	32.4	91–95
Port Sudan	19 35	37 13	35.1	89–95
Karima	18 33	31 31	30.2	86–95
Atbara	17 40	33 58	37.8	85–95
Khartoum	15 36	32 33	47.3	85–95
Kassala	15 28	36 24	37.8	85–95
Wad Madani	14 23	33 29	35.6	85–95
El Fasher	13 38	25 20	39.2	85–95
El Geneina	13 29	22 27	34.7	85–95
El Obeid	13 10	33 14	37.4	85–95
Kosti	13 10	32 40	38.7	85–95
Malakal	09 33	31 39	36.5	85–95

- Dust storms caused by steep pressure gradients for south and southwesterly winds south of the intertropical from which occur in the period May–October.
- Dust storms caused by the continental polar air reaching Sudan as cold fronts associated with strong eastern depressions. This occurs in the period February–April.

The maximum gust speed recorded for selected stations are presented in Table 4.

Wind energy has potential in regions of Sudan where the annual average wind speed exceeds $4\,m\,s^{-1}$, as in most parts north of latitude 12°′N, and along the lower Nile valley. The extracted energy ranges from 400 to 600 $kWm^{-2}\,y^{-1}$. However, southern regions have the poorest potential because of the low average wind speeds. Experience in wind energy in

Sudan started in the 1950s, as 250 wind pumps from Australian government were installed in El Gezira agricultural scheme. However, due to difficulties of obtaining spare-parts and to the availability of diesel pumps, the wind machines ceased working [1,8,32].

8. Wind pump technology development

In the last 15 years, the energy research institute (ERI) has installed 15 'CWD 5000' wind pumps from the Netherlands around the Khartoum area and to the north and east. At the present time, the ERI, in cooperation with the Sudanese Agricultural Bank (SAB), is planning a further 60 wind pumps for water pumping in agricultural schemes, as financial support becomes available.

A distinction should be made between two applications:

- water pumping for domestic water supply and cattle, for irrigation, drainage, prawn breeding and salt pans (25 machines as shown in Table 5) and
- battery charging for lighting, TV, radio, telecommunications, etc. (three systems are available) [4,10,31].

The wind pumps are categorised as

(1) low lift (<6 m), high volume applications (2 pumps are available);
(2) medium lift application (<50 m) (10 pumps);
(3) deep-well applications (>50 m) (more than 13 pumps).

Five of the wind pumps of Table 5 are locally manufactured by

(1) National Company for Manufacturing Water Equipment Limited (3 pumps).
(2) Sahara engineering Company (1 pump).
(3) University of Wadi El Neil-Atbara (1 pump).

Table 5
Wind machines installed in Sudan

Mark	Made in	Units	Rotor diameter (m)	Site	Date of erection
Wananchi 8	Kenya	2	2.4	Khartoum North	1987
Kijito 12	Kenya	2	3.7	Khartoum	1987
Kijito 16	Kenya	2	4.9	Shendi	1989
Kijito 20	Kenya	1	7.4	Shendi	1989
CWD	The Netherlands	10	5.0	Khartoum	1986
CWD	Sudan	5	5.0	1. Shambat	1987
				2. Karima	1996
				3. Toker	1996
Dempster	USA	1	3.0	Talha	1991
Southern Cross	USA	3	5.0	Wadi Halfa	1986

The basic purpose of the CWD programme of the mid-1980s was for wind energy to play a significant role in meeting the rural energy needs in Sudan. This depended on a new generation of low-cost wind pump designs, which should be simple enough for local manufacture to evolve. Therefore the CWD of the Netherlands carried out consideration R&D for the Sudan wind energy project. These activities resulted in the development of acceptable wind pump designs that are suitable for application in Sudan, though the range of application may still be limited to low/medium head situations [26].

Most of the wind pumps are performing well, yet still have difficulties due to factors such as

(1) wide range in wind conditions from low wind speed to desert storm;
(2) varied requirements of water;
(3) insufficient knowledge by the end users about site selection, such as wind turbulence, which requires continuous study and design changes to suit the customer requirements;
(4) the price of wind pumps is too high for further market penetration;
(5) lack of credit schemes for users and too little user orientation;
(6) lack of reliable cost effective wind pump designs for extension to certain market areas such as small farmers (needing small wind pumps), large irrigation areas, salt production and fish farms (needing large wind pumps with rotor diameter over 7.5 m).

9. Further development of wind pumps

Priority has to be given to further industrial improvement of the technology around Khartoum. Once the technology is sufficiently reliable, the focus has to shift to applications in more remote areas for irrigation and for water supply. The overall specifications of the CWD 5000 wind pump (Fig. 3), as modified by ERI, are

Wind machine
Rotor diameter = $\Phi 5$ m,
Number of blades = 8,
Tower height = 9 m,
Transmission = Crankshaft and connecting rod,
Safety mechanism = Furling system.
Pump
Diameter = $\Phi 76$ mm,
Stroke = 20 cm,
Static head = 20 m,
Cut-in wind speed = $4\,\mathrm{m\,s^{-1}}$,
Rated wind speed = $9\,\mathrm{m\,s^{-1}}$,
Cut-out wind speed = $12\,\mathrm{m\,s^{-1}}$.

Such modified wind were tested at the ERI-site at Soba, near Khartoum, and then, installed at Karima (2 pumps), and Toker (2 pumps). The most obvious region to enlarge the programme is the northern region because of a combination of:

(1) good wind regime;
(2) shallow ground water at 5–10 m depth;
(3) need for additional rural water supply;

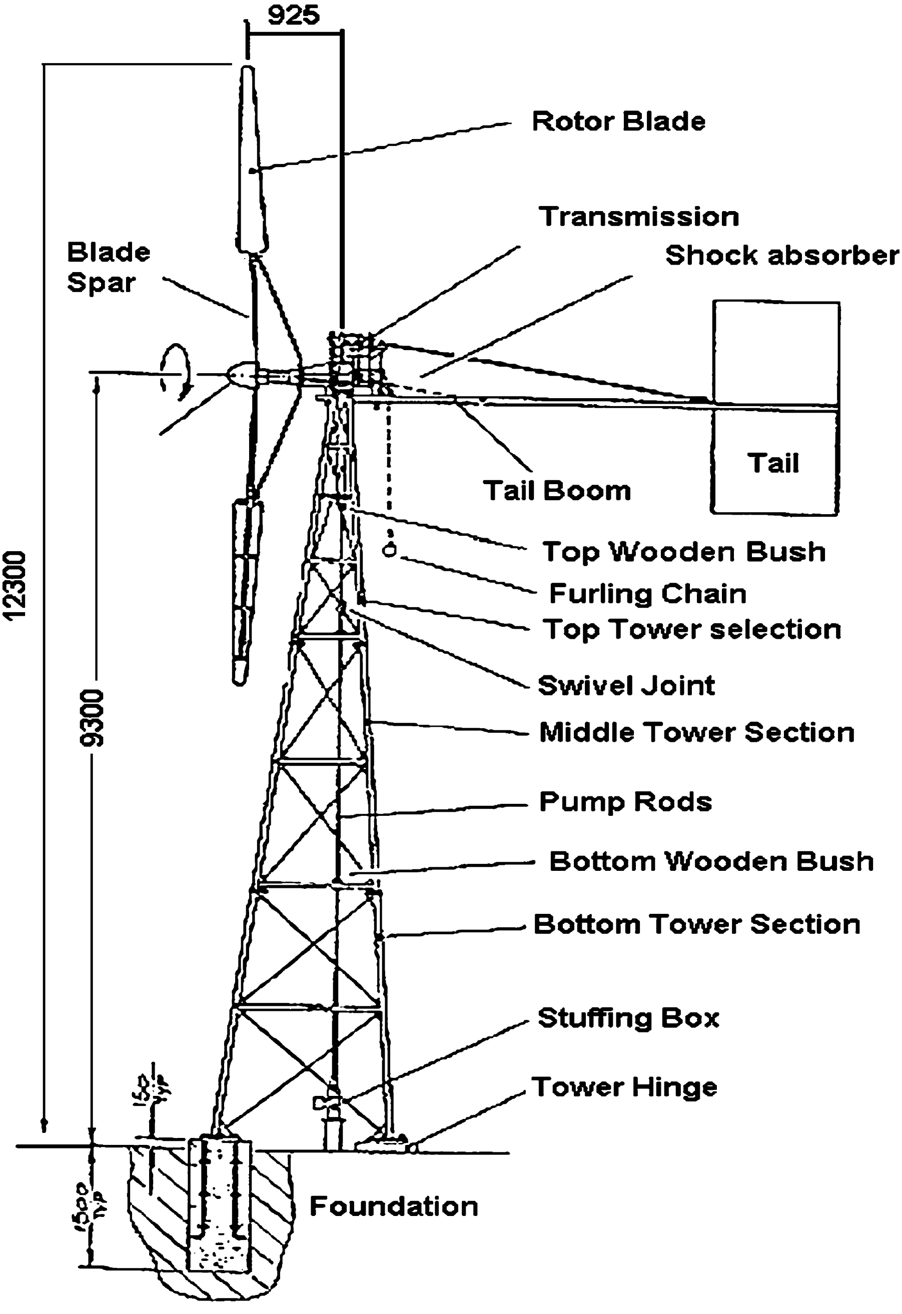

Fig. 3. Schematic of the construction of the wind pump.

(4) existing institutional infrastructure: National Company for Manufacturing Water Equipment Limited (NCMWE), Sahara Engineering Company, and Sudanese Agricultural Bank (SAB).

10. Sizing a wind pump

The size of a pump driven by a wind machine is a function of the pump head, the required water flow rate and the mean wind speed. The three main parameters that are needed are the total pumped head H (m), the pumped volume flow rate $Q\,(\mathrm{m^3\,s^{-1}})$, and the expected mean wind speed $V\,(\mathrm{m\,s^{-1}})$. The actual delivered power of the rotor must equal the required hydraulic power, so

$$\mathrm{C_p}\eta_\mathrm{m}(1/2\rho_\mathrm{air}AV^3) = \rho_\mathrm{w}gHQ, \tag{21}$$

where C_p is the coefficient of performance or efficiency of the rotor, η_m is the mechanical efficiency of wind pump, ρ_air is density taken to be $1.15\,\mathrm{kg\,m^{-3}}$, A is the rotor area in m^2, $\rho_\mathrm{w} = 1000\,\mathrm{kg\,m^{-3}}$ is the density of water, and $g = 10\,\mathrm{m\,s^{-2}}$ is the acceleration due to gravity. Rearranging gives

$$A = (1000 \times 10HQ)/(0.58C_\mathrm{p}\eta_m V^3) \tag{22}$$

and the rotor diameter follows from

$$D = \sqrt{\frac{4A}{\Pi}}. \tag{23}$$

The required water flow rate, the pump head and the wind speed will vary throughout the year, so it is convenient to estimate the means of each variable for every month. The daily demand for water is found from the likely per capita consumption either from: field measurements, or from internationally accepted minimum values. The head is the sum of the depth of the static water level below the surface, the maximum expected draw down, the height of the storage tank (if any) above the surface and any dynamic head losses in the delivery pipes. The wind speed should be measured at hub height or the standard height of 10 m. The rotor area is then calculated for each set of monthly values. The month, which needs the largest rotor area, is called the design month. This represents the worst case, for of the system can meet the requirements for this month it can meet them for every month. A value for C_p has to be chosen for these calculations and a convenient but realistic value would be 1/6 or 0.167 [34]. If the rotor diameter indicated by the design month is greater than 8 m, normally the maximum for a wind pump, then either the flow rate date should be checked, or consideration should be given to using more than one wind pump or other types of pumping scheme. Notice that both the water and the wind resource need to be quantified at the site where the wind pump is to be erected. If hydrological data is not available, test boreholes may have to be drilled to determine the depth of the water table. As water is pumped from the borehole, the water level will drop below the surrounding water table and this difference in levels, called the draw down, has to be taken into account when estimating the total pump head. The wind pump should be sized so that even in the windest conditions the flow rate pumped out of the borehole is not greater than the inflow into the borehole from the water table. This is usually not a factor in irrigation schemes, where the water source may be from canals, rivers, land drains or shallow wells. The daily water flow rate required for human consumption in a village or for cattle watering is easier to estimate than for irrigation purposes. The required flow rate will vary for different crops and types of soil and throughout the seasons. The amount of rainfall to be expected must also be taken into account. Further details of the complex calculations, which may be required, are given by Omer et al. [4]. The speed of rotation of the rotor of a wind pump

varies with the wind conditions and pumping requirement. Variable speed operation allows pumping over a wide range of wind speeds. Fig. 4 shows the final results of monitoring wind pump for the Soba site.

A sizing of wind pump for drinking and irrigation purposes usually requires an estimation of hourly, daily, weekly and monthly average output. The method for making such estimation is combining data on the wind pump at various hourly average wind speeds with data from a wind velocity distribution histogram (or numerical information on the number of hours in the month that wind blows within predefined speed). The result is given in Table 6, which gives the expected output of wind pump in various wind speeds and the statistical average number of hours that the wind blows within each speed range. The total output for each wind speed range is obtained by multiplying the output per hour at which that speed is likely to recur. By adding together the output for each speed range, the total annual output is obtained. The important of doing this monthly is that quite often, the least windy month will have a mean wind speed of only 60–70% of the annual mean wind. So, the available wind energy in the least windy month can be as little as 20% of that can be expected for a mean wind speed equal to the annual average wind speed. Therefore,

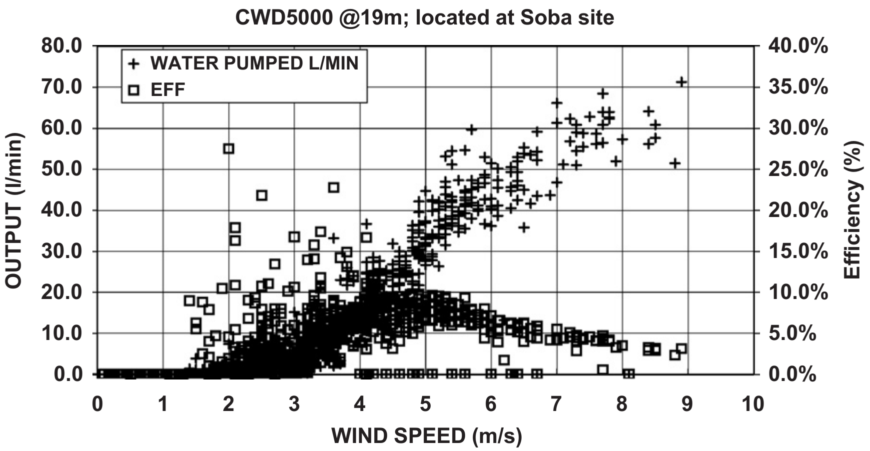

Fig. 4. Performance of the CWD 5000.

Table 6
Wind speeds versus wind pump discharges

Wind speeds ($m\,s^{-1}$)	Annual duration (h)	Output rate ($m^3\,h^{-1}$)
3.0	600	0.3
3.5	500	1.4
4.0	500	2.3
4.5	400	3.0
5.0	500	3.7
5.5	450	4.3
6.0	450	4.7
6.5	300	5.2
7.0	300	5.7

if annual averages are used, a considerable margin is necessary to allow for least windy month conditions. The total efficiency of energy conversion is between 7% and 27% based on using mean wind speed. The speed of the wind continuously varies. The actual energy in the wind is considerable greater than if the wind blows continuously at the mean wind speed. Maximum wind pump efficiency that can be obtained theoretical is 59.3% [19] known as Betz efficiency. The actual values that can be achieved practically are less than the above because of mechanical losses and aerodynamic problems, which are not considered in collecting the 0.593 values.

11. Cost comparison of diesel and wind pumps

Two systems are compared:

(1) A borehole of 35–40 m depth with a 18 HP = 13.3 kW diesel engine powered pump.
(2) A borehole of 25–30 m depth with a modified CWD 5000 wind pump.

A tentative cost comparison is shown in Table 7, using the formula

$$\mathrm{CT} = (A + F \times P + M)/V, \tag{24}$$

where CT is the total annual cost, and

$$A = [C \times I \times (I + 1)]^{T}/[I + 1]^{T-1}, \tag{25}$$

where A is the annual cost of capital [33], C is the initial capital cost, I is the interest rate or discount rate, and T is the lifetime. F is the total annual fuel consumption, P is the fuel cost per unit volume, M is the annual maintenance cost, and V is the volume of water pumped.

The comparison indicates that the necessary fuel and maintenance needed to run the diesel pump units long-term are the main lifetime costs, and not the capital cost of the diesel pump itself. In Sudan, where the fuel is expensive, the supply is uncertain, the infrastructure is poor, and where there are many populated remote areas, the following is concluded:

(1) the initial investment cost of wind pumps is too high; this may be a manufacturing scale problem;
(2) maintenance costs in some areas are too high for the user;

Table 7
Cost comparison of diesel and wind pumps in Sudanese Dinar (S.D.)

Specification	Diesel pump	Wind pump
Cost of borehole deep well	182,400	114,000
Cost of the system (purchased or fabricated in Sudan)	93,600	440,000
Cost of storage tank	—	420,000
Cost of annual fuel consumption	343,700	—
Cost of maintenance and repair	120,000	110,000
Total annual cost	1,582,100	1,084,000
Specific water pumping cost/S.D.	79/m^3	54/m^3

1 US$ = S.D. 250 (Sudanese Dinar), in January 2001.
Annual output 15,000–20,000 m^3 of water.
Annual fuel consumption: 490 gal (1 imperial gallon = 4.55 l) at price S.D. 475/gallon.

(3) the lifetime pumping costs are similar for pumping water by wind pump and by diesel pump;
(4) parallel and integrated projects could reduce costs;
(5) local production is favoured;
(6) utilities and water authorities should have responsibilities for technology and investment;
(7) there are substantial power production fluctuations due to variation in wind speed, and so using water storage is beneficial.

12. Constraints regarding the implementation of wind energy

There are numerous limitations to the implementation of wind energy programme in Sudan. The major problem is the inadequate provision of funds and the apparently high cost of locally manufactured wind machines. Most of the raw materials such as steel used in the manufacturing process are not locally available and therefore make a significant contribution to the cost. Nevertheless, the potential market for wind pumps appears to be high enough for emergence of a local wind pump industry in Sudan. This, however, requires the industry to have access to a mature technology and to be competitive (technically and financially) with existing pumps. Emergence of a local wind pump industry also depends on the dynamism of the local industrial sector in the national economy and the government support this receives.

13. Discussion

Making general conclusions about wind pumps in Sudan are limited by having only tested one type of machine (CWD 5000). Nevertheless, wind pumps are most appropriate at sites with good wind regimes (more than $4.0\,\mathrm{m\,s^{-1}}$), and low to moderate heads (less than 50 m). Such areas are generally on the north (along the Nile basin) and on the northeast of the country (Red sea hills).

The designers' performance predictions were overestimated by 30–50% for daily average wind speed of $3–5\,\mathrm{m\,s^{-1}}$; higher wind speed performance is impaired by rapid wear of the cup leather, which reduces the system operating efficiency. Optimally an efficiency of about 10% and a water output of about 30 l per minute have been achieved for wind speeds of about $4.5\,\mathrm{m\,s^{-1}}$. This efficiency was well below the designer/manufacturer's estimates. However, this might have been due to the following problems, which were frequently encountered on the field:

- wear of the front and rear transmission bearings;
- rapid wear of the leather cups.

The CWD 5000 has not proved to be a reliable, commercially viable design. After early problems with the furling mechanism and the pump itself were overcome, failures of the head frame assembly and the crank arm on many machines, proved that various design weaknesses urgently needed to be rectified. Nevertheless, there are technically appropriate applications in Sudan for well-designed, reliable wind pumps. The Kijito wind pumps, for

example has been field-tested in Kenya and Botswana and found to be a reliable (albeit expensive) machine.

The cost comparison table indicates that the necessary fuel and maintenance needed to run the diesel pump unit are the main factors that govern the overall cost, and not the capital cost of the diesel pump itself. The maintenance cost for the CWD 5000, however, was too high but this is entirely attributed to its bad design. Therefore, in the case of Sudan where the fuel is expensive, the supply is uncertain, the infrastructure is poor and areas are remote; the use of wind machines become more cost-competitive with diesel as the demand and head decrease and fuel prices and transport distances increase. The following can be deduced from the cost comparison case:

- initial cost of the wind pump was high compared to diesel pump;
- costs of the maintenance of wind pumps were exceptionally high;
- water pumping cost was more or less the same for both.

14. Conclusions

(1) Mean wind speeds of $4\,\mathrm{m\,s^{-1}}$ are available over 50% of Sudan, which suited for water lifting and intermittent power requirements, while there is one region in the eastern part of Sudan that has a wind speed of $6\,\mathrm{m\,s^{-1}}$, which is suitable for power production.
(2) The base case financial and economic analyses show that using wind pumps for remote rural water supply is cost-effective in cases where the (demand × head) product is less than $750\,\mathrm{m}^4$ for wind resources of over $4\,\mathrm{m\,s^{-1}}$.
(3) The initial investment cost of wind pumps is high, this entirely a scale problem and local mass-production facility would substantially reduce this capital cost.
(4) The substantial wind power fluctuations necessitate the use of large storage tanks. The setting up of manufacturing facilities for module easily assembled water tank is as important as the wind pump itself.
(5) According to the investigation on demand and purchasing power of the rural people, more than 60 wind pumps will be installed before year 2007. Thus the prospects for wind pumps are increasing.

15. Recommendations

The current analysis does not support the below-mentioned recommendations, which are also drawn from the author own experience. However, further research is needed to find out if such recommendations might be effective:

(1) The data presented in this paper can be considered as a nucleus of information for research and development of wind energy project; however, detailed investigation should determine the best specific sites.
(2) Local manufacturer, whenever possible, is recommended for wind pump systems. Low cost designs as well as reliable devices have to be provided.
(3) Government should consider a ‘water pumping wind machines programme’ as an infrastructure building programme and should both encourage village co-operatives and set up agencies for installing and maintaining wind pumps.

(4) Government should encourage wind energy systems in view of the environmental benefit.
(5) To attain exchange of knowledge and information, an international promotional group should be set up with its own office, newsletter and, for example, an annual workshop. For the long term, an association with a larger remit and having more power and contacts with other energy bodies needs to be established.
(6) Investment and more flexible licensing procedures, would encourage the private sector to assemble, install, repair and manufacture wind pumps.
(7) Reallocate Sudanese resources away from feeding wars and the arms industry towards real development, which will serve peace and progress.
(8) Finally, several automatic weather stations that record data on a temporal and spatial basis will be needed. These stations will be considered as complementary to the existing stations and will serve as a good source of information for statistical analyses and correlation among various stations.

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